Single-shot 3D imaging of fuel injection in a Spark-Ignited Direct-Injected Gasoline Engine

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Abstract
There are currently large efforts being made towards improving internal combustion engine efficiency without degrading engine performance. To do so, advanced combustion strategies that require in-cylinder fuel/air mixtures to be prepared with unprecedented care and exactness are being implemented. Spray-guided stratified-charge (SGSC) operation is an example of one such strategy that offers high efficiency under light-load operation but requires precise fuel injector and combustion chamber design to ensure robust engine performance. Understanding the instantaneous mixture formation processes aids in the success of such strategies and is therefore an important goal for internal combustion engine research. Direct visualization via optical diagnostics remains one of the most powerful tools for gaining insight into in-cylinder mixing processes, such as liquid fuel spray break-up. Although substantial efforts have been made over the last few decades to develop and implement liquid fuel spray diagnostics in the challenging in-cylinder environment, such techniques have been almost exclusively 2D or too complex to be used regularly in design practices. Only now are practical, commercially available 3D visualization technologies beginning to mature to a level for which they can be adapted to perform in-cylinder diagnostics. Here we demonstrate the promise of using a single plenoptic camera technique for visualizing in-cylinder fuel sprays in 3D by imaging fuel spray development within an optically accessible SIDI engine that is operated under a variety of conditions relevant to conventional homogeneous-charge and SGSC engine strategies.

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Introduction

Spark-ignition direct-injection (SIDI) engines for passenger vehicles are increasingly gaining market share due to their benefits of increased fuel economy and lower emissions [1]. However, reliable ignition and combustion stability under stratified-charge operation remain technological challenges that need to be addressed [2]. At light and medium loads, some SIDI engines run at stratified-charge mode where fuel is injected into cylinder just before ignition, creating an ignitable fuel-air-residual mixture around the spark plug and leaner further away. In this way, the combustion mixture is prepared globally lean and unthrottled operation is realized, resulting in fuel efficiency that is significantly improved relative to conventional strategies. At high load, the SIDI engine operates conventionally and burns a homogeneous-charge of stoichiometric composition in order to obtain a better power output.

Direct injection (DI) of fuel into the combustion chamber offers the flexibility that is required to tailor the fuel-air-residual mixture from highly stratified to nearly homogeneous as needed, to ensure favorable ignition and combustion over the engine’s wide range of speeds and loads. While DI liquid fuel sprays introduce a strong momentum into the chamber, fuel spray penetration, break-up, and dispersion are not only driven by the spray itself but also by the in-cylinder gas flow, both by the bulk flow characteristics [3] as well as by per-cycle variations [4]. The stochastic nature of the turbulent in-cylinder flow [5] and fuel spray in turn lead to variations in ignitability, combustion phasing, and efficiency.

A large body of published work over the past decades has demonstrated that understanding the mechanics of the fuel-air-residual mixing processes is key in enabling optimal SIDI engine design. In this context, (laser-) optical diagnosticians have significantly contributed towards the development of direct-injection engines [6, 7]. Advances in pulsed lasers, sensitive imaging detectors, and research on a wide range of spectroscopic techniques provided the means for imaging measurements of in-cylinder processes with high temporal and spatial resolution, and more recently also with very high image frequencies. Typically, though, such measurements have either provided planar (2D) images or have required averaging techniques [3]. Only a few examples of 3D imaging techniques have been demonstrated. For example, instantaneous flame emission images were recorded in 3D in an engine with a fiber-based detection system [8], a laser and camera cluster were used to image fuel via laser-induced fluorescence of a tracer [9], and the 3D motion of a flame front has been tracked within a spark ignition engine [10].

The shortcomings of using planar-imaging techniques to study complex three-dimensional processes can be substantial, especially when considering the out-of-plane motion and gradients that are so characteristic of the turbulent, in-cylinder environment. Therefore, efforts are being made towards improving the capabilities of instantaneous 3D imaging techniques for in-cylinder measurements in engines. Typically, such measurements have been impeded by the expense of equipment and the impracticality of using multiple cameras or lasers within the space limitations associated with optical engines. Further, the technical expertise required to operate such systems can be limiting in itself. Seeking simpler solutions for instantaneous 3D imaging is therefore of great interest.

Light field or plenoptic technology offers the potential to achieve single-camera, volumetrically resolved imaging capabilities, even when optical access is limited. Light field imaging concepts were first proposed over a century ago [11]. At that time the basic concept of utilizing a light field image and the spatial and angular information contained within to obtain 3D information was described. In principle, any normal digital camera can be transformed into a plenoptic camera by simply placing a micro lens array in front of its photosensor. By doing so, the regular main lens produces a real image in front of the sensor, which is then projected onto the photosensor by the array. In this manner, each micro lens produces an image of a subsection of the object from a unique perspective, which can be reconstructed in 3D by post-processing. Developments in camera and computer technologies over the last two decades have accelerated the evolution of light field imaging. A plenoptic camera with lenticular array located at the sensor plane and reliable depth estimation was first demonstrated in 1992 [12] and since, a handheld prototype plenoptic camera has been built by modifying an existing digital camera without altering the operation of the camera [13].

Improved depth-resolution was achieved with a multi-focus plenoptic camera that utilizes a multi-focal length micro lens array [14]. Currently, commercial software can be used to generate 3D reconstructions from raw plenoptic images. However; such software has been optimized for images taken of opaque objects with high contrast surface features. Therefore, the software works very well for most solid body photography applications but is challenged by the translucent objects commonly found in combustion scenarios, such as sprays and flames. The applicability and limitations of plenoptic imaging towards translucent scalar distributions with present state-of-the art reconstruction approaches was recently presented [15]. As expected, some limitations were recognized while trying to volumetrically reconstruct chemiluminescence and laser-induced fluorescence images taken of flames and jets. New reconstruction approaches are currently being researched to overcome such limitations. Recently, plenoptic imaging systems were demonstrated capable
of reconstructing global spray features of automotive fuel sprays [16]. In this study, the automotive fuel spray proved a more suitable object than flames or highly atomized sprays, largely due to the semi-opaque nature of the dense liquid core region of the spray. Spray angle measurements have been taken and validated by comparison with traditional 2D imaging techniques using Mie scattering under static operating conditions [16].

In this study, the ability of a plenoptic imaging system to visualize liquid fuel spray development from an automotive fuel injector in an operating SIDI engine in 3D is tested. The system’s capability to capture spray structure, including the stochastic spray deflections that occur due to cycle-to-cycle variability in spray-flow interactions are demonstrated. Testing is performed under both homogeneous-charge and stratified-charge motored engine conditions, and also under high and low in-cylinder swirl conditions in order to provide distinct DI spray development differences than may be recognized.

Experiment

Engine details

The 3D spray imaging tests were performed in a prototype, four-stroke, four-valve optical single-cylinder SIDI engine. The engine consists of a pent-roof combustion chamber cylinder head, which houses a closely spaced fuel injector and spark plug. The eight-hole injector delivers a symmetric fuel spray pattern with nominal spray angle of 90°. Extensive in-cylinder optical access is realized through two cylinder head windows, a transparent quartz cylinder liner and a piston window [4]. The key geometric measurements and operating parameters of the engine are listed in Table 1. Two start of injection (SOI) timings were used, 300°BTDC (before top dead center compression) and 35°BTDC. The former injection timing is conventional; because it begins early in the intake stroke the air and fuel mixture has adequate time to mix well into a homogeneous-charge before the power stroke begins. The latter injection timing begins late in the compression stroke as is typical for stratified-charge operation. A throttle valve in one of the two intake ports allows the in-cylinder flow to be controlled. When the throttle valve is held wide-open low-swirl, tumble-dominated operation is achieved with a swirl ratio (SR) of 0.8. When the throttle valve is closed swirl-dominated flow is achieved and the SR increases to 5.5 [3].

All of the spray tests were performed under motored, non-firing engine operation whereas the ignition was withheld. Figure 1 shows the layout of the engine cylinder head as well as a raw spray image taken from the plenoptic camera. All of the images presented in this paper were taken from this same perspective, viewing the injector directly through the piston window.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>86 mm</td>
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<tr>
<td>Stroke</td>
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<tr>
<td>Clearance Volume</td>
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<td>Engine Speed</td>
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<tr>
<td>Intake Air Temperature</td>
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<tr>
<td>Intake Air Motion</td>
<td>Low and high swirl</td>
</tr>
<tr>
<td>Start of Injection (SOI)</td>
<td>300°BTDC (Homogeneous-Charge Mode), 35°BTDC (Stratified-Charge Mode)</td>
</tr>
</tbody>
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Table 1. Engine parameters and experimental conditions

![Figure 1. Layout of engine head geometry with spray image example as seen from below (left) and schematic side view (right)](image)

Plenoptic imaging setup

A 29-megapixel plenoptic camera (Raytrix R29) was used to image the laser-induced Mie scattering signals generated by the fuel sprays. The spray was viewed from the perspective shown in Fig. 1 through the quartz-insert piston window with the Bowditch arrangement [17] shown in Fig. 2. A 527 nm Nd:YLF laser (Quantronix, Darwin Duo) with pulse energy set to 0.2 mJ was used for illumination. The natural divergence of the laser beam allowed the green light to ex-
pand without further beam manipulation to illuminate the spray from the side, through the transparent cylinder liner and head window.

The imaging rate was limited by the camera’s readout frequency to one frame per every two cycles. The camera was synchronized to the fuel injector but not directly to the laser. The laser ran independently at 10 kHz, which ensured that only a single pulse occurred within each 110 µs camera exposure. The resulting temporal accuracy of the images was less than a single CAD at 1300 RPM, which was adequate for this study. It would be possible to phase lock the camera to the laser if greater temporal accuracy was desired. Spray images were taken at several different timings, which are all reported in terms of crank angle degrees (CAD) after start-of-injection (aSOI). At least 100 spray images were taken for every condition so that the cyclic variability of the spray could be analyzed. All of the 3D data reconstruction and some of the data post-processing were performed with RxLive (Raytrix) and the rest of the 3D post-processing was done in Matlab.

**Image analysis**

Plenoptic imaging efforts to date have primarily focused on 3D imaging of non-transparent objects, whereas contrast and opacity unambiguously defines the depth information necessary for 3D reconstruction. Conversely, translucent objects, such as sprays or flames create a more ambiguous light field because the light that they generate originates from both internal and external features along the objects third-dimension. Unfortunately, algorithms haven’t been designed yet for the specific task of translucent object 3D reconstruction; so instead the algorithms built into RxLive (Raytrix) software package have been utilized for this study. Despite being designed primarily for solid-body imaging applications, this software has proven capable of doing a reasonable job at reconstructing in-cylinder fuel spray geometry in 3D [16]. The following procedures, as summarized in Fig. 3, were used to process all of the plenoptic images presented in this study.

The raw Mie scattering images (a) were pre-processed with RxLive to increase their brightness and contrast to better emphasize the high contrast features of the spray. Previous studies have shown that doing so increases the accuracy of the 3D reconstruction procedure [15]. The images are then reconstructed in RxLive; the result of which is a 3D point field containing hundreds of thousands of 3D data points which represent the location of the liquid fuel spray, not to be confused with individual liquid fuel droplets. These 3D point fields can be displayed in 2D as a “depth point map” as is shown in (b). However, with so many data points these maps are challenging to interpret so a depth-fill interpolation algorithm was applied to the images to create a smoother “depth map.” Finally, any unwanted structural background generated by the cylinder head features are removed by a custom Matlab code, the results of which is a depth map with all its focus drawn to the spray itself, as is shown in (c). Notice that a color/intensity scale has been provided for the reconstructed images (b) and (c). The color/intensity scale was determined to an accuracy of ±2% by performing a calibration procedure that involves traversing a target through the camera’s depth of field, as has been demonstrated in previous studies [16]. The depth of field of the camera is larger than 80 mm, which is more than adequate to capture the fuel sprays entire penetration into the engine.

![Figure 2. Experimental setup for 3D spray imaging system](image-url)

![Figure 3. Overview of the image processing steps used to generate 3D spray images](image-url)
Results

Before performing the engine tests, static spray images were acquired with the engine in a stationary state. The results of three fully processed 3D depth map images of the sprays development under static conditions can be seen in Fig. 4. The timing of these images has been labeled in terms of CAD at an assumed engine speed of 1300 RPM so that they can be directly compared with the complementary engine images.

![Figure 4](image)

**Figure 4.** Depth map images under static (no in-cylinder flow) conditions. The spray plumes have been numbered to assist the discussion

Homogeneous charge preparation

The engine was run in homogeneous-charge operation by injecting fuel early during the intake stroke (SOI at 300 BTDC), which ensures a nearly homogeneous fuel/air mixture around the normal time of ignition. Figure 5 shows depth map results at three timings following injection at both 800 and 1300 RPM, and at both swirl levels for the latter. The state of the intake port, either open or closed, is indicated for each condition in the left column of Fig. 5. Remember that high in-cylinder swirl occurs when the throttle valve is used to close one of the two intake ports.

With such early injection, the momentum of the intake air-flow jet is high and subsequently the in-cylinder flow interacts strongly with the developing fuel spray. Notice how prominent the effect of the flow-spray interaction is in the high swirl, 1300 RPM, condition shown in Fig. 5(a). In order to fully appreciate the effect of the in-cylinder flow on the homogeneous-charge sprays, the centerline jet trajectories of the static spray images were extracted from Fig. 4 and are superimposed onto Fig. 5 in the form of dashed lines. By comparison, plumes 2, 3, 4 can be recognized to have been rotated clockwise by the swirling airflow. The incoming intake jet violently pushed plume 1 counterclockwise towards plume 8, whom has been disrupted itself by the flow in a similar manner.

Notice that the spray deflections are much less prominent in both the low swirl, 1300 RPM, condition shown in Fig. 5(b) and the high swirl, 800 RPM, condition shown in Fig. 5(c), as is expected. All three homogeneous-charge conditions tested show shorter spray penetrations depths than were seen in the static tests presented in Fig. 4. This reduction in penetration is due to both the momentum exchange that occurs between the spray and the in-cylinder flow and also due to the slightly elevated temperature (45 °C) of the engine tests relative to the static tests (20 °C).

Stratified charge preparation

The engine was run in stratified-charge operation by injecting late in the compression stroke (SOI at 35 bTDC), which ensures that a partially premixed cloud exists in the vicinity of the spark plug around the normal time of ignition. With such late injection, the structure of the spray is not only affected by the in-cylinder flow but also the elevated in-cylinder pressures and temperatures. Also, with the piston closer to TDC the spray is more susceptible to interactions with the piston bowl. The spray imaging results for the stratified-charge conditions are shown in Fig. 6.

These images reveal that the stratified-charge spray is only minimally influenced by in-cylinder motion. The stratified-charge sprays shown in Fig. 6 are closer in appearance to the static sprays shown in Fig. 4 than the homogeneous-charge sprays in Fig. 5. This is to be expected, as the in-cylinder flow momentum and turbulence intensity present at the time of stratified-charge injection is far reduced from what it was during the intake stroke due to dissipation occurring over the compression stroke. The plume trajectories under both the low and high swirl conditions look very similar to those observed during the static injection tests (ref. Fig. 4) because under both conditions the fuel jets development is dominated by the momentum of the spray, not the in-cylinder flow.

The increased in-cylinder pressure (840 kPa compared with 92 kPa during the intake stroke) and complimentary increase in temperature led to the visible reduction in the stratified-charge sprays penetration rate. When compared to Fig. 4 and Fig. 5 it can be seen that the stratified-charge spray penetrations are less than either the homogeneous-charge or the static sprays. In addition, the stratified-charge spray is more compact (smaller plume angle) than the other sprays due to the higher in-cylinder air pressures and densities.
Figure 5. Instantaneous 3D spray images for the early injection, homogeneous-charge operating condition. The overlaid dashed-lines represent the centerline jet trajectories of the spray under static (no in-cylinder flow) conditions. In addition, the outlines of the intake valves are labeled to indicate whether or not the valves port is open to flow.

Figure 6. Instantaneous 3D spray images for the late injection, stratified-charge operating condition.
Figure 7. Examples of cyclic variation in spray structure for the early injection, homogeneous-charge operating condition.

Figure 8. Examples of cyclic variation in spray structure for the late injection, stratified-charge operating condition.
**Cycle-to-cycle variation in spray geometry**

In order to examine the cyclic variability of spray geometry over the various conditions, Figs. 7 and 8 show examples of triplicate instantaneous depth field images taken during different engine cycles for select timings and operating conditions. While the current sample size is not large enough for quantitative results to be drawn, some qualitative observations can be made. The spray structure varies significantly from cycle-to-cycle, particularly at the higher engine speeds and higher swirl flow conditions. Either decreasing the engine speed or reducing the in-cylinder swirl levels reduces the variability in spray structure. The stratified-charge sprays were more stable than the homogeneous-charge sprays, as is expected due to the differences in in-cylinder thermodynamic condition and flow intensity between the two conditions.

**Summary**

A plenoptic imaging system was used to visualizing liquid fuel spray development with-in a spray-guided, spark-ignition, direct-injection engine in 3D over a variety of operating conditions. The expected impact of engine speed, injection timing, and in-cylinder air motion were clearly observed in the single-shot images. The practical, single-camera technique demonstrated its ability to capture 3D structural information about in-cylinder fuel sprays which may be used to guide engine research and design.

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**References**